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Sub-Nanometer Interferometry and Precision Turning for Large Optical Fabrication

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SUB-NANOMETER INTERFEROMETRY AND PRECISION TURNING FOR LARGE OPTICAL FABRICATION

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Abstract
At Lawrence Livermore National Laboratory (LLNL), we have the unique combination of precision turning and metrology capabilities critical to the fabrication of large optical elements. We have developed a self-referenced interferometer to measure errors in aspheric optics to sub-nanometer accuracy over 200-millimeter apertures, a dynamic range of 5×10^{-9}. We have utilized diamond turning to figure optics for X-ray to IR wavelengths and, with fast-tool-servo technology, can move optical segments from off-axis to on-axis. With part capacities to 2.3-meters diameter and the metrology described above, segments of very large, ultra-lightweight mirrors can potentially be figured to final requirements.

1 INTRODUCTION

Over the past 30 years, diamond turning has been used for a select set of metallic optical fabrications. The strengths of the process are that it: 1) is cost effective compared to the alternatives; 2) applies small forces to the optic during fabrication, which is critical for lightweighted parts; 3) is an excellent figuring process for visible or shorter wavelength applications, reducing the role of polishing to meeting the surface finish requirement without impairing the figure. The limitations are that the materials must be 'diamond-turnable' [1] and the optical design must allow turning on an available machine tool. These two limitations can be addressed in two separate ways. Non-axisymmetric optics can now be turned on a lathe with the addition of a high-bandwidth, third linear axis, usually called a fast tool servo. This axis can then position the tool dependent on spindle angular position and allow rotationally non-symmetric optical prescriptions and turning off-axis segments of larger optics on axis. This second case is of interest for large lightweight optics because each off-axis segment of a larger conic mirror can be turned on a diamond turning machine.

The usual materials for diamond turning are nonferrous alloys such as copper, brass, electroless nickel, and aluminum [1]. Historically, to use a lightweight structural material such as beryllium, a turnable material had to be deposited on the optic and figuring occurred in this material. While this is unlikely to succeed on a cryogenic application such as NGST, it has been successful in more moderate environments. An all aluminum mirror, using a metal foam sandwich construction, would be a viable solution for a cryogenic application. Finally, direct figuring in materials such as beryllium is possible with more robust turning tools and grinding heads. Much of the precision of diamond-turning will carryover although the surface finish may be degraded.

Finally, the most critical component of a fabrication process is the metrology that enables an accurate part. Well characterized machines are very repeatable and part accuracy must come from proper metrology. A self-referencing interferometer has been developed that can measure accurately to sub-nanometer values. As with traditional interferometers, measurements are fast and post-processed data provides useful feedback to the user. The simplicity of the device allows it to be used on large optics and systems and, by stitching data, fairly large aspheric departures can be characterized.

In this paper, complete solutions for fabricating large lightweight optics are not presented. However, the array of capabilities in precision fabrication and metrology that apply to the problem is discussed. The opportunity presented is to integrate very high accuracy metrology with high precision fabrication methods. The key is that the infrastructure for these solutions exist and so no new facilitization is required to implement these technologies.

2 LLNL PRECISION ENGINEERING

The history of precision engineering at LLNL is of course rooted in research and development supporting the Nuclear Weapons Complex of the U.S. Department of Energy. The purpose of this activity was to improve the precision with which parts could be fabricated and inspected at the weapons laboratories and production plants. While initial work involved improving existing commercial machines, it soon became necessary to design and build special purpose machine tools directed specifically at the unique requirements at hand. An expertise in high precision machine tool design developed under interesting constraints: we hardly ever build more than one of any machine that we design and therefore the machine must basically work the first time.

At about the same time that this machine expertise was developing, researchers were investigating the application of single-crystal diamond tools as a method to enable extremely accurate fabrications. These two activities led to a series of diamond turning machines that were simply not available in the commercial sector. Additionally, design and fabrication of inspection machines and the application of commercial machine tools became necessary to serve LLNL programmatic needs.

The current portfolio of projects in Precision Engineering at LLNL is quite diverse. In addition to traditional work for the Weapons Program, much of the

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support goes to the Laser Program, which has several large efforts underway currently, including the National Ignition Facility and an extreme ultraviolet lithography project. Both of these programs require precision engineering support for fabricating and mounting high precision optical components. Other programmatic support goes to the Physics and Space Technology Directorate, working on manufacturing concepts for very high energy colliders for high energy physics applications, and to the Biology and Biotechnology Research Directorate on a project to map the human genome.

2.1 Infrastructure for Optical Fabrication

One of the advantages of having a long history in a discipline is an accumulation of equipment and experience that can then be applied to current problems. At LLNL, we have an array of diamond-turning machines with part capacities up to 2.3-meter. The machines and some general capabilities are listed in Table 1. A small machine of interest is the PERL II which is a very accurate small T-base lathe with surface finish capabilities below 25 Å rms; surfaces with 7 Å rms surface finish have been generated on the machine under ideal conditions. Diamond Turning Machine 2 (DTM-2) is a mid-sized machine built on a Moore #3 base and with an oil shower for temperature stability. The unique feature of DTM-2 is the rotary axis under the tool, which allows the tool to rotate under computer control. This eliminates tool non-roundness errors since the same part of the tool can be used to generate a complete part path. DTM-4 is in the conceptual design phase and will likely replace the capabilities of DTM-2 while giving better surface finish and precision.

Table 1: Summary of precision turning machines.

Machine	**Work Volume** (Dia. x Length, m)	**Accuracy** (nm P-V)	**Finish** (Å rms)
PERL II	0.15 x 0.1	100	25
DTM 2	0.50 x 0.5	500	300
LODTM	1.65 x 0.5	100	50
DTM 3	2.30 x 1.0	600	250
DTM 4*	0.30 x 0.3	100	50

* DTM 4 is in the design phase and is expected to be online in 2 years.

Of course the machines that apply most to the current problem of large lightweight optics are Diamond Turning Machine 3 (DTM 3), with the largest part capacity, and the Large Optics Diamond Turning Machine (LODTM), widely believed to be the most accurate large machine tool in the world. DTM-3, shown in Figure 1, is a T-base configuration machine with laser interferometer feedback and straightedge and yaw compensation of each axis [2]. The machine has a horizontal axis spindle that can swing a part of 2.3-meters diameter. Using the tool-set station on the machine, diameters can be cut to sub-micrometer absolute *accuracy*. A perfect application for this capability is the mandrels for grazing incidence telescope mirrors; the EUVE mirrors described below were turned on DTM-3 and control of size was important on that project. The most noticeable aspect of DTM-3 is the 400 gallons per minute of mineral oil that showers the part and all critical machine components. This oil shower does an excellent job of removing heat from local heat sources and shielding the machine from ambient temperature swings, which are kept below +/- 0.25 C.

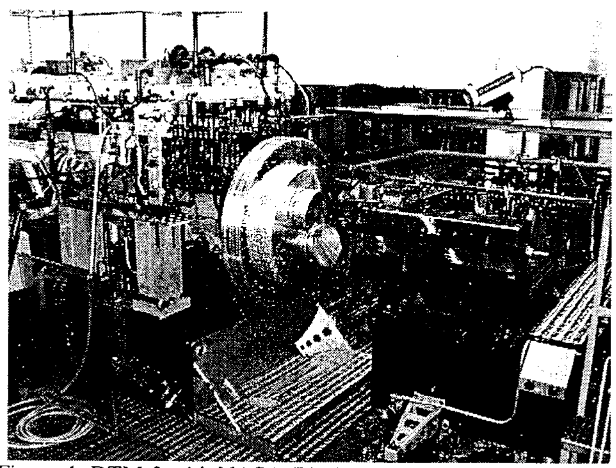


Figure 1. DTM-3 with NASA /UAH's SPARCLE optics.

The LODTM is shown in an artist's conception in Figure 2. The machine has a vertical spindle axis with the toolbar traversing in x and z on a bridge over the spindle [3]. The heart of the machine's accuracy is obtained from the Super-Invar metrology frame that reads all critical error motions, including those in the spindle, and compensates the tool path to eliminate these errors. With this concept, we can get by with a mild steel weldment for the machine frame. Temperature stability is handled with milli-degree air temperature control in the room and in the cooling panels around the metrology frame. While the machine was built to fabricate the Alpha chemical laser optics, it has been used to fabricate other parts such as the infrared secondary mirrors for the Keck Telescope and off-axis conics for SPARCLE, a low-cost, space lidar experiment to measure wind speeds on earth, which is led by NASA and the University of Alabama, Huntsville.

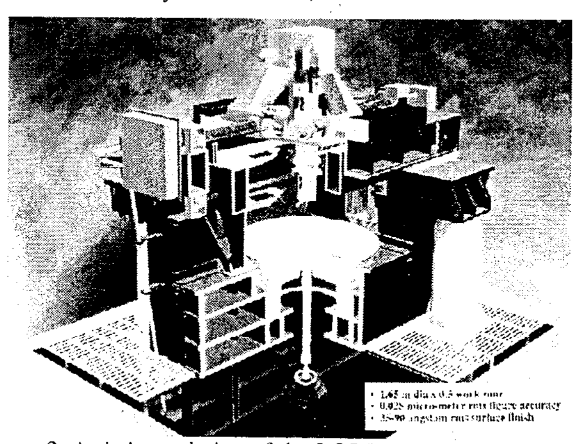


Figure 2. Artist's rendering of the LODTM.

The other necessary component to successful high precision fabrications, whether they are optics or nuclear weapons components, is the experience base that resides with the personnel that maintain and operate the machines. The success of high precision fabrications requires the application of lessons learned in part design, fixturing, and cutting parameters from previous projects.

2.2 Previous Instrument Projects

While the primary focus of the Precision Engineering efforts at LLNL has been in support of the Nuclear Weapons Complex, there have been projects outside of that arena. Some of the ones that apply to the fabrication of large lightweight optics are described below. While some of these are optical fabrications, others are complete instrument design, fabrication and test.

XMM Reflection Grating Spectrometer

The X-ray Multi-Mirror Mission is a soft x-ray astronomical mission led by the European Space Agency. The fabrication of the three grazing incidence telescopes was completed in Europe but the two spectrometers were the responsibility of the NASA-funded U.S. consortium of Columbia Astrophysics Laboratory, UC Berkeley Space Sciences Laboratory, and LLNL. One of the instruments is shown in Figure 3. The design is based on 200 replicated grazing incidence gratings that are flat to less than 0.6-micrometer (1-λ) in the critical dispersion direction. Obscuration is kept very low allowing the telescope to perform imaging and spectroscopy simultaneously. The gratings are replicated on silicon carbide substrates and installed on four points (non-kinematically to allow twist to be removed) in a high stiffness beryllium structure that is open on one end to interferometrically measure the gratings during installation. The structure is mounted to the spacecraft bulkhead with titanium bipod flexures that utilize constrained-layer damping to achieve high dynamic stiffness and yet exactly constrain the grating array. All design was completed at LLNL and vendors were developed to perform all of the individual fabrications, the substrates, the ruled master, replication of the gratings, and the beryllium structure. One instrument was assembled at LLNL and one at Columbia University. Both have been tested to better than 4 arc-sec half-energy-width (HEW) performance and the satellite will be launched in January 2000.

Extreme Ultraviolet Explorer (EUVE) Mirrors

An example of LLNL's fabrication capability was demonstrated in support of NASA's EUVE, which was launched in 1992 to make an all-sky survey using both spectroscopic and wide-band observations over the extreme ultraviolet region. LLNL diamond turned the grazing-incidence optical surfaces for the three scanning telescopes and turned and polished the optical surfaces for the spectrometer telescope. The spectrometer mirrors began as aluminum substrates whose surfaces were first rough-turned on the large diamond turning machine, DTM3. The optical surfaces were then plated with electroless nickel after which, the coated substrates were returned to the diamond-turning machine. The nickel coating was added because it presents a surface which diamond turns and polishes to higher quality than the aluminum substrate itself. Approximately half of the nickel was then removed in the second diamond turned operation, which produced the final figure within the nickel coating. Then the surfaces were polished to a surface roughness of approximately 15 Å rms. The polishing process used a compliant lapping surface whose shape and motion were arranged according to a wear model (in the form of the Preston wear equation) to remove an equal amount of material from all parts of the optical surface. The object was to improve surface finish while preserving the form as diamond turned. The optical figure was periodically monitored throughout polishing using an in-situ profiling instrument to ensure that the optical form did not degrade. After polishing, the mirrors were gold plated to enhance their reflectivity at EUV wavelengths.

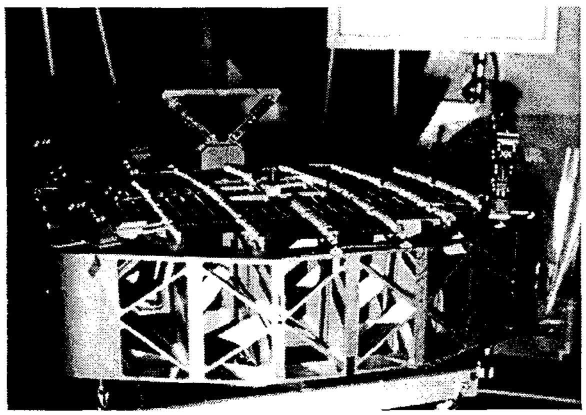


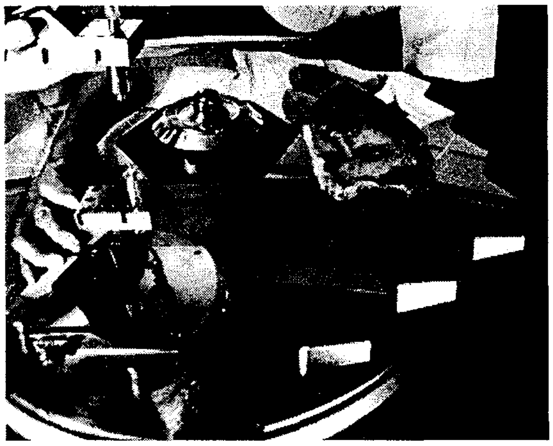
Figure 3. The XMM RGS array.

Keck Telescope Secondary Mirror

The Keck telescopes on Mauna Kea in Hawaii are a well-known astronomical tool. For infrared wavelengths, with the addition of adaptive optics, the performance will soon be better than can be attained with the Hubble Space Telescope. The secondary mirrors for the Keck telescopes are lightweighted beryllium structures with electroless nickel coating. The mirror, shown in Figure 4a, has an irregular shape that is similar but slightly smaller than the image of the primary. The purpose for this overfilled aperture is to reject stray light disturbances that may intrude on the desired image. The final figuring of these mirrors required diamond turning without polishing due to the associated roll-off problems. The nickel overcoat was diamond turned on LODTM at LLNL with final peak-to-valley figure errors less than 80-nanometers, as shown in Figure 4b.

Alpha Chemical Laser Optics

The Large Optics Diamond Turning Machine (LODTM) was designed specifically to diamond turn and inspect the metal aspheric optics for the Alpha chemical laser. These requirements led to a work volume of 1.65-meters diameter and a 0.5-meter height plus a vertical spindle to minimize errors due to gravity sag. For the copper clad Alpha surfaces, figure accuracy of 28-nanometer RMS and 35-90 Å rms surface finish have been obtained. The new challenge for LODTM is to diamond turn and inspect aspheric optical surfaces similar to the original Alpha, but this time in silicon.



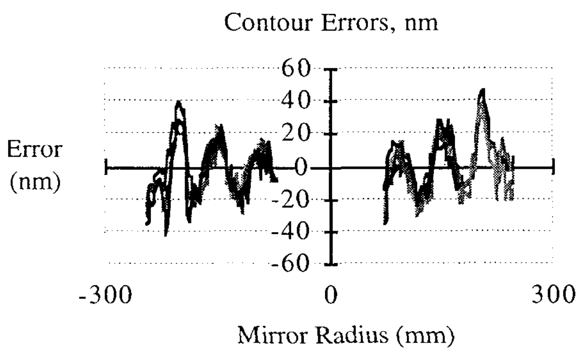


Figure 4. (a) One of the Keck secondary mirrors and (b) error data from several radial contours.

3 ADVANCED INTERFEROMETRY METHODS

Visible light interferometry is the metrology of choice for optical fabrication for several reasons: the unit of measure is the wavelength of light (~500nm) which is stable, traceable and can be further subdivided to give increased resolution; the surface of the optic under test can be spatially sampled at many points ($>10^6$) simultaneously; the data acquisition time is typically less than one second; and customized phase extraction algorithms can be used to minimize the effects of instabilities and non-linearities.

Over the past several years a new interferometer has been developed that provides sub-nanometer accuracy and is easily configured to operate under extreme environments with minimal real estate. Commensurate software has also been developed to permit the measure of aspheric surfaces. These properties support the use of this technology for the fabrication and testing of aspheric mirrors at cryogenic temperatures for future space telescopes.

3.1 Phase Shifting Diffraction Interferometry

The interferometer described here is based on diffraction[1]. Diffraction is a fundamental process that permits the generation of arbitrarily perfect spherical wavefronts over a specific numerical aperture by using a circular aperture with a radius comparable to the wavelength of light λ. For example, if the aperture has a radius of $2\lambda_v$ then the deviation of the diffracted wavefront from spherical is less than $\lambda_v/10{,}000$ over a numerical aperture of 0.3 in the far field of the aperture. Using this principle, *two independent* wavefronts can be generated - one serves as the measurement wavefront and is incident on the optic or optical system under test and the other serves as the reference wavefront. Since they are generated independently their relative amplitude and phase can be controlled, providing contrast adjustment and phase shifting capability. This concept can be implemented in several different ways using lithographically generated apertures or single mode optical fibers. The most versatile and the one described here is based on single mode optical fibers which provide the diffracted wavefronts.

Figure 5 shows the basic principle of operation. Light is launched into two single mode optical fibers. Light leaving the end of each fiber diffracts to a spherical wavefront over an extended angular range. The measurement wavefront is incident on the optic under test, is aberrated and comes to focus on the face of the other fiber. This aberrated wavefront reflects from a semi-transparent metallic film on the face of the fiber and interferes with the reference wavefront to produce the interference pattern. The simplicity of the interferometer is obvious - only two single mode optical fibers (sources of the measurement and reference wavefronts) and the optic under test. The critical component is the face of the fiber with the semi-transparent film. It must have a flatness

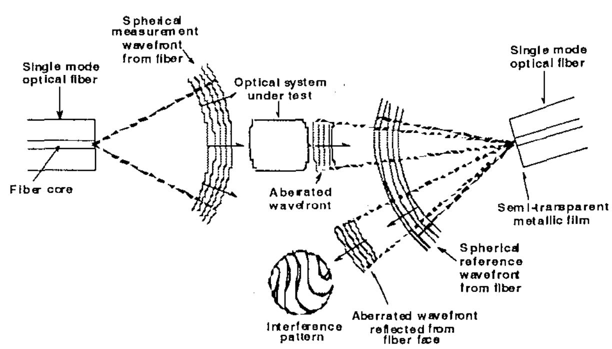


Figure 5. Principle of operation of the phase shifting diffraction interferometer using single mode optical fibers (not to scale).

1 Parts of this article were presented at the OSA Annual Meeting, Portland (1995) and the OSA Topical Meeting on Extreme Ultraviolet Lithography, Boston (1996).

comparable to the desired accuracy of the measurement, but only over a very small area around the core of the fiber. This is realized by embedding the fiber in a glass substrate and superpolishing the entire assembly.

The complete interferometer with phase shifting and contrast control is shown in Figure 6. The interferometer can be configured in one of two ways depending on the conjugates of the component or system being measured. Figure 6a shows the interferometer configuration for testing optics where the ends of two fibers are placed at spatially separated conjugates. Here two temporally incoherent beams are launched into separate equal length fibers. One beam is first reflected from a retroreflector mounted to a piezoelectric phase shifter[2] and the other beam is delayed by a path length equal to the optical path length between the faces of the fibers. The half wave plate is used to adjust their intensity ratio to give unity visibility in the interference pattern.

Figure 6b shows the interferometer configured for testing optics where the end of the fiber is placed at a common conjugate. In this configuration two temporally incoherent beams are launched into the same fiber. The beam delay is now equal to the round-trip distance between the fiber face and the optic under test. Interference on the CCD camera takes place between the phase-shifted wavefront that is reflected from the optic under test and the delayed wavefront directly from the fiber. Maximum visibility is now one half. In both configurations the optic under test (exit pupil) is imaged onto the CCD camera. Data acquisition and analysis are similar to other phase shifting interferometers.

Note that in each configuration the quality of the wavefronts before they are launched into the fibers is not important because the fibers act as spatial filters. Equally important is the fact that the measurement and reference wavefronts encounter no other optical components that can degrade accuracy before they interfere, except the face of one fiber which must be flat over a small area around the core as noted above.

3.2 Accuracy

A direct determination of the accuracy is always difficult. Since accuracy of the interferometer is based on the calculated sphericity of the measurement and reference wavefronts, experimental verification puts a lower bound on the accuracy. A test was conducted to determine the quality of the wavefronts from the fibers. It consisted of launching beams into two fibers of equal path lengths and letting the two diffracted wavefronts interfere directly on the CCD camera. This was done for different angular shears of the diffracted wavefronts. If the wavefronts are truly spherical the optical path difference should be independent of angular shear over the full field. After subtracting the theoretical two-point interference pattern from actual measurements, the wavefront difference was less than 0.06-nanometer rms.

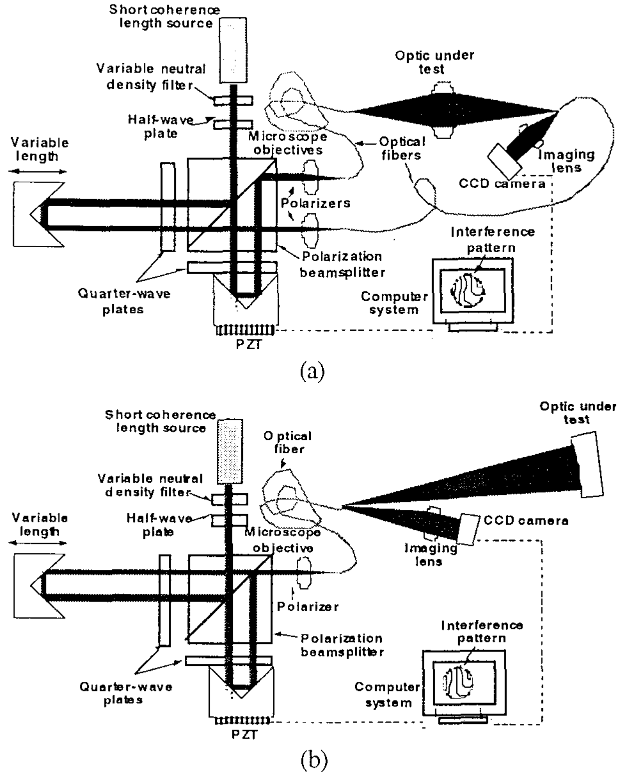


Figure 6: Two configurations of the phase shifting diffraction interferometer for measuring optics at: (a) distinct conjugates; (b) a common conjugate.

3.3 Testing

Several extreme ultraviolet (EUV) lithographic optics have been measured including complete projection systems and aspheric mirrors. One of particular interest was an all spherical, two mirror, four reflection, ring field EUV projection system. The interferometric setup was similar to Figure 6a where the two fibers are placed at the conjugate positions of the imaging system. The measured wavefront in the exit pupil, expressed as a 36 term Zernike fit (piston, tilt and power removed), is shown in Figure 7. The wavefront error is 1.44-nanometer rms.

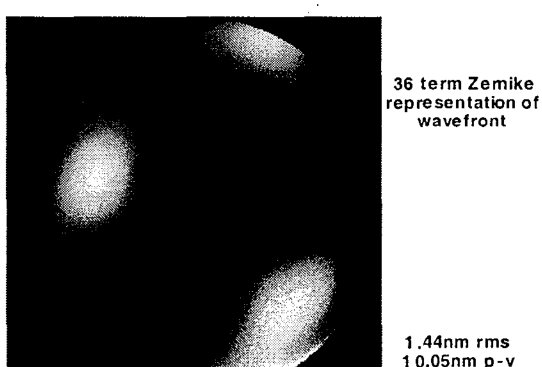


Figure 7. The measured wavefront in the exit pupil of an EUV ring field projection system with piston, tilt and power removed.

2 Phase shifting can also be accomplished by axially translating either fiber, but the phase shift is not uniform across the spherical wavefront.

Figure 8 shows the measurement of a mirror with an aspheric departure of 10-micrometers. For this particular mirror, the surface gradient produced an interference fringe density that exceeded the Nyquist sampling of the CCD array. It was therefore necessary to take two interferograms at different axial positions of the mirror to acquire data over the entire clear aperture. The interferograms were then stitched together to reconstruct the mirror surface. The theoretical aspheric equation was then subtracted from this result revealing a figure error of 0.95-nanometer rms.

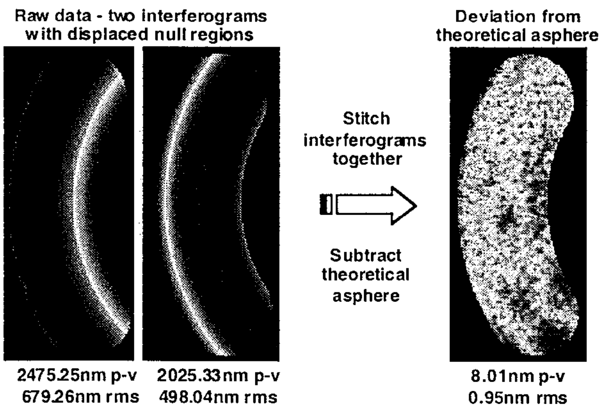


Figure 8. Measurement of an aspheric mirror that required data stitching due to a 10μm aspheric departure.

4 APPLICATION TO LARGE, ULTRA-LIGHTWEIGHT OPTICS

The class of large space optics of current interest must be separated into cryogenic and moderate temperature applications. The requirements of the two cases are just too different to apply a common design and material choice to both. Of course the choice of fabrication processes is more likely to be affected than the metrology methods. Below we discuss the application of the technologies from LLNL to the fabrication and testing of large, lightweight space optics. An important point is that little new development is required to implement this technology, keeping risk and cost low.

Interferometry

Accurate metrology such as the phase shifting diffraction interferometry described here is the key to the success of optical fabrications. It provides not only the verification of success but also feedback information in an in-process fashion. The technology has been demonstrated on small, very high accuracy aspheric optics with a dynamic range of 5 x 10^{-9}. Some degradation in this performance will occur as measurable portions of the mirror are stitched together to generate a complete image. The stitching process has been demonstrated with little loss of fidelity.

For cryogenic measurements, the interferometer can be implemented quite simply. The only penetration into the cryostat is one single-mode optical fiber. Of course room temperature measurement can be made in a vacuum chamber in a similar manner. In either case, it would be important to test the sensitivity of the mirror to variations in operating temperature around the nominal. The phase shifting interferometer should perform this measurement quite accurately since there are no reference optics in the varying environment.

Finally, the cost of the interferometer is low enough that multiple copies are a reasonable approach. Therefore, it is likely that units would be required at the location(s) of the final optical figuring and polishing and at the final verification site to test a full aperture mirror. In addition, if a precision pre-figuring operation were necessary, an interferometer would allow more accurate figuring at this stage, thus reducing the cost of the final figuring. This pre-finishing step may require a longer wavelength interferometer to measure larger errors and for a non-reflecting surface in the visible. A factor that must be overcome at longer wavelengths is the lower spatial resolution of infrared detectors.

Measurements should be made with a horizontal optical axis so that the mirror will suffer the minimum gravity sag on a kinematic mount. These mounts would likely be designed similar to the XMM array bipod flexures shown in Figure 3. The advantage of these mounts compared to traditional ball/vee mounts is there is no unpredictable friction, only some stiffness which can be well characterized. This mount stiffness would then input to a finite element calculation that would allow the effects of gravity to be removed from the measurement.

Mirror Fabrication

The choice of a mirror fabrication process is heavily determined by the design and material choice of the mirror. The common basis of the solutions proposed here are the large diamond turning machines at LLNL to take cost advantage of the installed infrastructure. The actual cutting process would depend on the chosen material. Of course diamond-turnable materials such as aluminum would allow the use of single-crystal diamond tools. More difficult materials such as beryllium could be machined with polycrystalline tools of diamond or CBN and still take advantage of the inherent accuracy of the diamond turning machine. Beryllium and ceramic materials such as silicon carbide could be figured on the machines with diamond wheels on a grinding head. These options are presented in order of our experience base with the process. We have fabricated many optics with the traditional diamond turning methods. Turning beryllium has been done at LLNL for other non-optical applications but never of the size and surface finish quality currently required. Optical grinding on smaller turning machines has also been done but not on the high performance materials required here.

Depending on the details of the final solution, modifications to the machines would be fairly minimal. The LODTM currently operates near the current state-of-the-art for its type of fabrication. DTM-3 in its current configuration is very repeatable and this is the requirement for fabrication with accurate metrology methods. The surface finish of DTM-3 is certainly less than desirable and there are probably some areas for improvement here. Surface finish will also be impacted by the necessary addition of the high bandwidth axis, the fast tool servo.

The fast tool servo is a necessary addition to the current capability to allow large conic mirror segments to be fabricated on axis. Once this capability is realized, it provides complete flexibility in optical prescription up to the spatial bandwidth of the system. This application of a fast tool servo is not new. A very high precision, short travel, fast tool servo was part of the original LODTM design [4] to correct high bandwidth errors. In fact the original device is currently being reinstituted on LODTM to allow for compensation during cutting of the silicon Alpha optics. Using fast tool servo technology to make off-axis aspheric optics on axis has been done at the Department of Energy nuclear weapons laboratory at Oak Ridge, Tennessee [5]. Significant work in fast tool servo development and application has also been done at North Carolina State University [e.g.6].

Cryogenic Applications

Obviously, the most critical aspect of a cryogenic mirror is its susceptibility to the difference in fabrication and operating temperature. Two designs bear consideration. The first is an all aluminum mirror using a sandwich construction of two thin facesheets around either an aluminum foam core or a hexagonal-cell machined structure. The aluminum foam core is available from several vendors in the U.S. down to 3 or 5 percent relative densities. The hexagonal structure design takes advantage of the development of high speed machining of aluminum for the aircraft industry, where high cutter velocities result in low applied forces and therefore allow very thin webs. In either case, brazing the facesheets to the core would be done with an aluminum braze alloy to eliminate the problems with mismatched thermal coefficients of expansion. With an all aluminum mirror, final figuring would be via traditional diamond turning. If the final surface finish is insufficient for the application, a development effort may be possible. An area to investigate is to eliminate the growth of aluminum oxide on the freshly cut surface with the application of a cutting fluid during turning or cutting in a zero-oxygen environment [7]. The advantage of using aluminum is the simplicity and likely cost savings of working with a well-characterized material.

The second design to consider is probably more conventional for space applications, using beryllium for the mirror material. The difficulty is that beryllium has not been successfully figured with single-crystal tools. We can still take cost advantage of the diamond turning machines, using them in a semi-finish figuring role, prior to final finishing. The cost of many finishing processes scales directly with the quantity of material to be removed and so by achieving tighter tolerances at the semi-finish stage, costs can be reduced significantly.

Moderate Thermal Applications

The reduced constraints that come as a result of a more moderate thermal environment will simplify fabrication, reducing cost and risk, and will allow a higher performance optical surface. The optical material with which we are most familiar is electroless nickel, which can be both diamond-turned and polished. Of course anytime that materials with different expansion rates are combined in a single structure, there will be changes in the equilibrium state as a function of temperature. Large scale (long spatial wavelength) figure changes are not a problem if a figure measurement can be made at the operating temperature. Then, as long as the figure variation due to operating temperature variation is not too severe, the design will be functional. Small scale deformations, such as would occur across a single hexagonal cell in a honeycomb design, are indeed a problem because these errors cannot be removed during an iterative figuring/measuring operation.

The choice of substrate material would at first seem to be quite straightforward. Beryllium offers very high stiffness to weight advantages with good thermal characteristics. Although we have used beryllium extensively at LLNL, contending with its hazardous nature is difficult. Also, large blanks of beryllium with the best properties may be unobtainable. This may push the size limitation from the finishing machine to the blanking operation. Silicon carbide is of course a candidate substrate material with excellent stiffness to density properties. However, it too can be quite expensive to fabricate into large structures. Finally, we have made optics with aluminum substrates and nickel finished coatings. Examples of this method are the SPARCLE optics for NASA's Marshall Space Flight Center and the EUVE telescopes. In this case, the amount of nickel can be minimized by diamond turning the aluminum prior to plating, allowing a very accurate although cost effective substrate.

5 CONCLUSION

We have presented tools that have been developed at LLNL and have application to the fabrication of large, lightweight reflective optics. The advantage of these technologies is that they require little new development to apply them to the current problem. Therefore, the cost and risk associated with these solutions are both relatively low. Beyond these capabilities, LLNL also offers a vast experience base in areas such as chemistry, material science, and optical design.

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